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EFFECTS OF BIOKARSTIC PROCESSES ON THE DEVELOPMENT OF SOLUTIONAL RILLENKARREN IN LIMESTONE ROCKS

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ABSTRACT

Karren landforms developing on limestone rocks are understood to be produced primarily by chemical dissolutional processes. Available data suggest that rainfall intensity, drop size, water temperature and viscosity play significant roles in the growth of the most simple of these features, which are termed rillenkarren. Nevertheless, chemical data and scanning electron microscopy provided by our study have shown that mechanical removal of small limestone particles is one of the principal processes involved in the growth of rillenkarren. This mode of detachment is caused by the impact of raindrops but their effect seems greatly increased when algal cells of *Chroococcus minutus* (Kütz.) Näg. have previously corroded the surface of the limestone, weakening its crystalline structure. These fragile micromorphologies of biokarstic origin are fundamental in the development of rillenkarren, complementing the wellknown physico-chemical controls that are involved.

KEY WORDS exokarstic processes; biokarst; rillenkarren; controlled experiments; Western Mediterranean

INTRODUCTION

Rillenkarren are one of the most distinctive karstic landforms (Bögli, 1960; Sweeting, 1972; Perna and Sauro, 1978; Bögli, 1980; Ford and Williams, 1989). In spite of being the most simple solutional landforms to develop on inclined limestone, gypsum and salt rock outcrops, the processes involved in their development are quite complex (Glew and Ford, 1980; Ford and Lundberg, 1987). Rillenkarren consist of sets of small, packed and parallel, linear flutings (Figure 1), with lengths up to 50 cm and a characteristic width of 1·5 cm in some Mediterranean karstic landscapes such as the mountains of Mallorca, Spain (Ginés, 1990). These flutings are non-Hortonian channels (Horton, 1945) and start from the crests of the outcrops, showing typical herringbone patterns.

Rillenkarren have been explained in the literature (Bögli, 1980) as a strictly physico-chemically controlled type of solutional feature frequently found on bare limestone rock surfaces exposed to rainfall. Recent research has demonstrated that biological processes are important for many karstic phenomena (Viles, 1984; Trudgill, 1985) but rillenkarren are usually found on 'bare' rock surfaces (Folk *et al.*, 1973).

Simulations with an artificial rainfall machine and plaster models have shown that there is a strong dependence of rillenkarren characteristics on factors such as raindrop size and surface slope (Glew and Ford, 1980). Morphometric studies along climatic gradients have also stressed the role of temperature (Bordoy and Ginés,1990; Ginés, 1990). Apparently, the best developed rillenkarren in the northern hemisphere occur on southern exposures (Heinemann *et al.*, 1977) of sharp rocky surfaces without significant vegetation cover. In Mediterranean climates, rillenkarren are abundant on the widespread 'grey' limestone surfaces which lack the characteristic pitting and blackish colour that has been associated with biological phytokarst (Viles, 1984; Folk *et al.*, 1973). In such periodically arid environments, however, microscopic observation is necessary to determine whether algae and lichens, both epilithic and endolithic, are truly absent.

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Figure 1. Typical appearance of rillenkarren. Scale bar 3 cm

Occasional observations gave us evidence of unexpected biological phenomena related to the development of rillenkarren. We have thus developed some preliminary experimental studies of the processes involved. It was assumed that experimental procedure does not exactly reflect the natural conditions, but can presumably yield some estimation on this respect.

METHODS

In the Tramuntana Mountain Range, Mallorca, we collected rainwater samples from a variety of natural limestone surfaces. It was found that waters running off bare rillenkarren exposures contained significantly more detrital residues than waters from limestones observed to be well colonized by endolithic lichens (Fiol *et al.*, 1992).

In order to investigate these differences quantitatively, three experimental limestone surfaces, taken from the same Lower Jurassic limestone outcrop, were set up in an environmentally controlled cabinet (Conviron CMP 3244) for 217 days, with conditions fixed at 18–22°C, 90% relative humidity, and 14 h daylight with a maximum intensity of 14 000 lux: (1) artificially polished rock, (2) bare with rillenkarren, (3) lichen-covered. The surface area was $0{\cdot}13\,m^2$. A fine spray of 15 ml nutrient solution (Hoagland and Arnon, 1950), never exceeding $1{\cdot}5\,mg\,l^{-1}$ alkalinity, was applied daily to the colonized surfaces to maintain the metabolic processes of resident microorganisms. Because of the progressive decay in the values of alkalinity through sampling, the nutrient concentrations were increased (see arrows in Figure 2).

At approximately 2-week intervals, each surface was subjected to a simulated rainstorm using 500 ml of distilled water (intensity $30\,l\,h^{-1}$, depth 3·8 mm; velocity and raindrop size were not determined, although it was presumably somewhat greater than natural rainfall). Samples (250 ml) of run-off were taken for pH, conductivity and alkalinity determinations. Alkalinity was determined by colorimetric titration (APHA, 1976) using mixed bromcresol green/methyl red indicator solution and 0·01 N HCl (dissolved limestone (DL)). Because titrated samples regularly changed colour, additional titrations were made every 24 h on the same water sample, to determine the presence of fine micritic particulate limestone (PL). Filtered samples

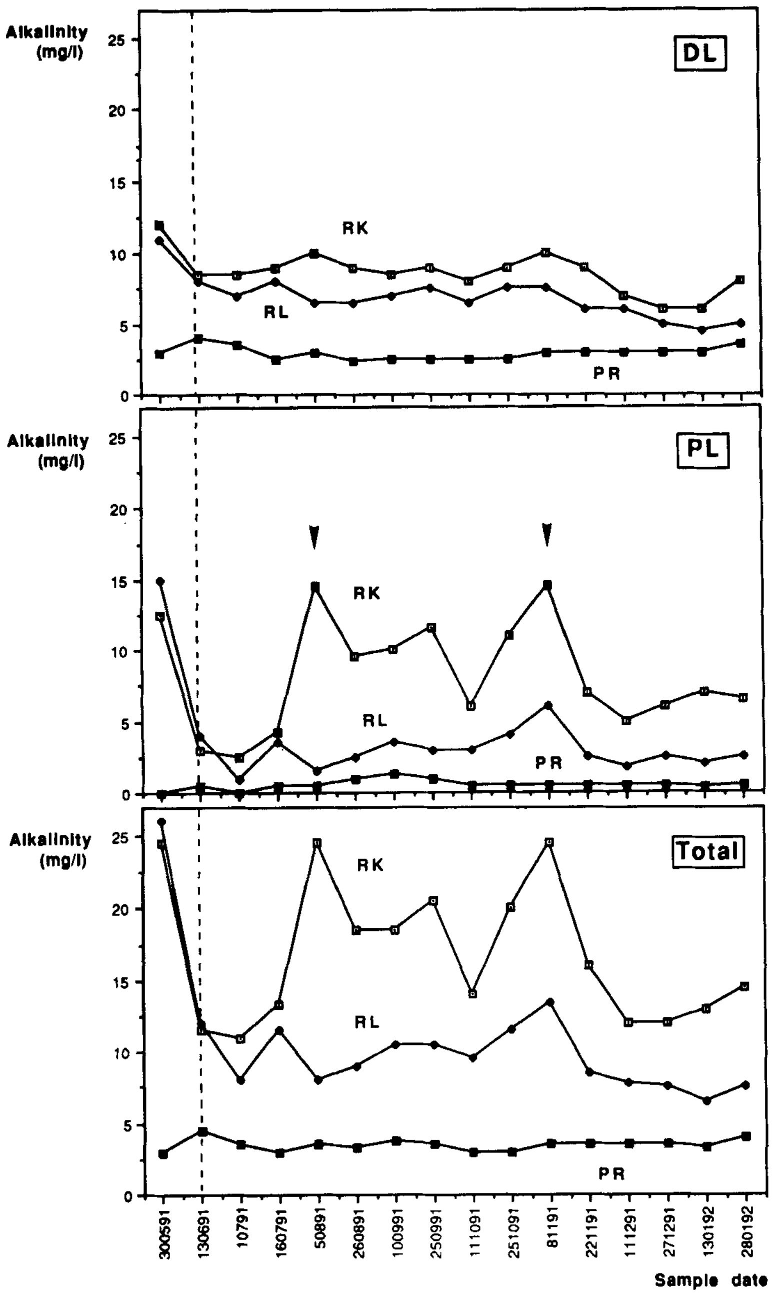

Figure 2. Alkalinity values of dissolved limestone (DL), particulate limestone (PL) and total observed during the experiment in the climatic chamber. Dashed line indicates the start of controlled experimentation parameters. Arrows mark the variation of nutrient characteristics. (RK, bare rock with natural Rillenkarren; RL, lichen-covered limestone; PR, artificially polished unweathered limestone)

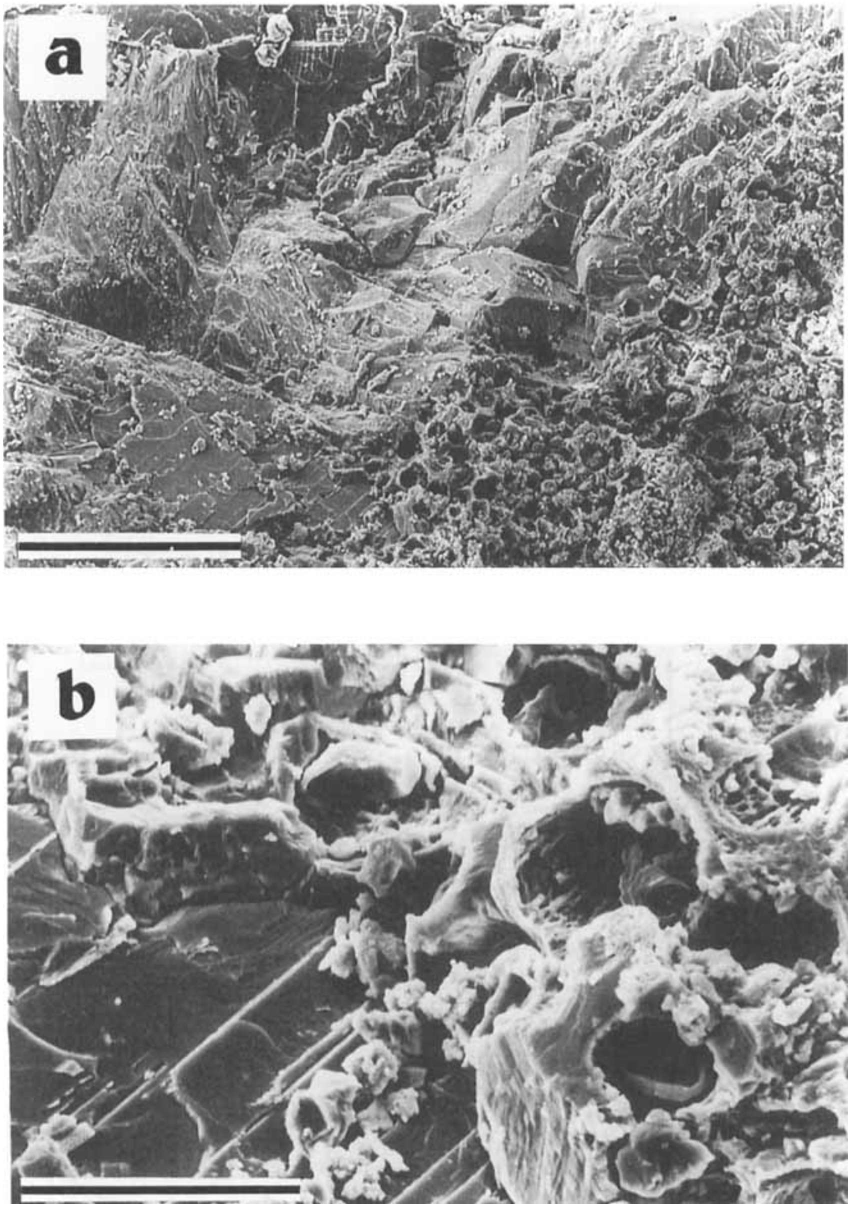

Figure 3. (a) SEM graph showing surface area increase (lower right corner) due to biological action with the characteristic borehole development. Scale bar 100 μm. (b) Detail of (a), note the presence of blue-green algae in the borehole. Scale bar 20 μm

(Whatman GF/C; 0·4 μm) never show colour shifts after the first titration. The remaining water was then systematically filtered for light microscopy and scanning electron microscopy (SEM).

RESULTS AND DISCUSSION

The fresh polished limestone displayed a relatively constant rate of dissolution of the rock (DL) of 2·92 mg l^{-1} (standard deviation (s.d.) 0·46; standard error (s.e.) 0·11, Figure 2). Particulate matter (PL) also showed uniform behaviour throughout the experiment, with very low values (mean 0·54 mg l^{-1}; s.d. 0·33; s.e. 0·08).

Table I. Values of rock lost ($g\,m^{-2}\,a^{-1}$) (DL, dissolved limestone; PL, particulate limestone)

	DL	PL	Total
Bare rock with rillenkarren	1·60	1·52	3·11
Lichen-covered rock	1·27	0·68	1·95
Artificially polished rock	0·54	0·10	0·64

This suggests that controls on the dissolution of the rock, which was entirely physico-chemical on this sample, were kept constant throughout the experiment. Particulate removal by raindrop impact (Brandt, 1990) was minimal, and can be attributed to the microtopography resulting from imperfect polishing as observed by SEM (Fiol *et al.*, 1992).

On bare rock with natural rillenkarren (Figure 2, RK) the DL values measured were: mean 8·59 $mg\,l^{-1}$; s.d. 1·49; s.e. 0·37. Those of PL were: mean 8·18 $mg\,l^{-1}$; s.d. 3·85; s.e. 0·96. As shown by optical microscopy and SEM observations, these much higher values can be attributed to endolithic activities of the blue-green alga *Chroococcus minutus* (Kütz.) Näg. (Fiol *et al.*, 1992). It has a characteristic dual effect which micritizes the rock (Figure 3), increasing contact surface areas accessible for dissolution and weakening the crystalline cohesion (Danin, 1983; Viles, 1987). As a result of this biological action, a characteristic microtopography develops which is highly vulnerable to raindrop impact. Cultures derived from scrapings of fresh karren samples have also yielded other algae. The more frequent are the blue alga *Chroococcopsis* sp., and the chlorophycean *Klebsormidium flaccidum* (Kütz.) Mattox et Blackwell, and *Apatococcus lobatus* (Chod.) B. Petersen.

The values obtained for the experimental lichen-covered limestone (bearing *Verrucaria calciseda* DC., *Petractis clausa* (Hoffm.) Kempelh, etc.) (Figure 2, RL) for DL were: mean 6·84 $mg\,l^{-1}$; s.d. 1·54; s.e. 0·38. Those for PL were: mean 3·64 $mg\,l^{-1}$; s.d. 3·25; s.e. 0·81. The lower values for the lichen-covered rock when compared with those from bare rock with rillenkarren may be due to the fact that, despite the micritization caused mainly by endolithic lichens, the mechanical effects of raindrop impact are lower because of floral shielding (Pomar *et al.*, 1975). This is more obvious in the case of PL than in that of DL, where the two values are similar.

SEM observations of filters show that the particles knocked off the experimental bare rock with rillenkarren are less than 5 μm in size and crystal aggregates (ranging from 20 to 75 μm) with blue-green algae, mainly *Chroococcus minutus*. On the experimental lichen-covered surface the crystal aggregates do not show blue-green algae.

The quantitative importance of diverse microorganisms on the formation of superficial karren under our experimental conditions is evident in Table I, and one may presume that they contribute significantly to processes previously ascribed to merely hydraulic phenomena. Also clear is the importance of PL, which is of a similar quantity to that of DL in the case of rillenkarren surfaces. Values obtained for PL imply that there is an effective doubling of the rate of formation of this kind of karren. Thus, the notable acceleration of rillenkarren development is due to the loss of a particulate fraction, a phenomenon which must be added to the well-established dissolutional processes that are recognized for this type of karstic weathering (Ford and Lundberg, 1987).

CONCLUSIONS

Our experimental work has demonstrated that biokarstic processes can influence the quantity of rock eroded by raindrops during the formation of rillenkarren. Probably since rillenkarren features form well on gypsum without any biological intervention, literature reviews have generally neglected the possible influence of algae. Our observations and experiments lead to a wider conception of biokarstic dynamics on apparently bare limestone outcrops. Rillenkarren are partly the result of the metabolic activity of microalgae. In these preliminary measurements, nearly half the natural material eroded from rillenkarren was derived from

detrital disintegration. This process does not affect rill morphology as intensively as in the case of 'Black' phytokarst from tropical limestone areas. 'Grey' phytokarst activity appears to be significant on rilled limestone surfaces in climates such as the Mediterranean, which are characterized by hot and dry summer seasons.

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